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ANALYSIS OF THE OPPORTUNITIES AND TRADE-OFFS FOR AN 48V ELECTRIFIED AIR PATH

Yang Liu
University of Bath
Bath, United Kingdom

Ramkumar Vijayakumar
University of Bath
Bath, United Kingdom

Richard Burke
University of Bath
Bath, United Kingdom

ABSTRACT

The electrification of powertrains is now the accepted roadmap for automotive vehicles. The next big step in this area will be the adoption of 48V systems, which will facilitate the use of technologies such as electric boosting and integrated starter-generators. The introduction of these technologies gives new opportunities for engine airpath design as an electrical energy source may now be used in addition to the conventional mechanical and exhaust thermal power used in super- and turbochargers. This work was conducted as part of the EU funded project “THOMSON” which aims to create a cost effective 48V system enabling engine downsizing, kinetic energy recovery, and emissions management to reduce the environmental impact of transportation. The paper presents a study on an electrified airpath for a 1.6L diesel engine. The aim of this study is to understand the design and control trade-offs which must be managed in such an electrified boosting system. A two-stage boosting system including an electric driven compressor (EDC) and a variable geometry turbocharger (VGT) is used. The air path also include low and high pressure EGR loops. The work was performed using a combination of 1D modelling and experiments conducted on a novel transient air path test facility.

The simulation results illustrate the trade-off between using electrical energy from in the EDC or thermal energy in the turbocharger to deliver the engine boost pressure. For a same engine boost target, the use of the EDC allows wider VGT opening which leads to lower engine backpressure (at most 0.4bar reduction in full load situation) and reduced pumping losses. However, electricity consumed in EDC either needs to be provided from the alternator (which increases the load on the engine) or by depleting the state of charge of the battery. The location of charge air coolers (pre- or post- EDC) is also investigated. This changes the EDC intake temperature by 100K

and the intake manifold by 5K which subsequently impacts on engine breathing. An experimentally validated model of a water charge air cooler model has been developed for predicting flow temperature.

1 INTRODUCTION

Vehicle hybridization and electrification technologies has become the most significant trend in powertrain development [1]. Turbochargers and after-treatment devices have made equally significant contributions to improving efficiency and reducing emissions [2-3], however, turbocharger has its own compromises which include poor performance in low engine speed, high torque operating conditions, delayed transient response (turbo-lag), and increased engine back-pressure [4]. To overcome these shortfalls, many different technologies related to boosting system are being considered. The use of VGT and multistage turbochargers are favoured approaches in the last few years. They can improve the transient performance in low speed region, also increase the low speed torque, however, due to the limitation of mechanical design, there are still some working conditions that they struggle because of the limited exhaust gas energy. The design of the wider air path system, including the location of boosting devices, intercoolers and EGR valves, are investigated by other researchers [5-7]. Electric boosting systems have been studied in the researches [5-7] this approach offers a new degree of freedom into the airpath where modest amounts of electrical energy can be deployed.

The aim of this paper is to investigate the opportunities and design and control trade-offs associated with an electrified boosting system comprising a turbocharger and electrically driven compressor. Section 2 of this paper presents the background information specific to electrified air-paths. Section

3 then presents the candidate air-path, simulation model, and the experimental facilities. Section 4 presents the results of both simulation and experimental work and finally, conclusions are indicated in section 5.

This work was conducted as part of the EU Commission funded Thomson Project (<http://www.thomson-project.eu/>, grant number 724037). The project aims to increase the market penetration of 48V hybrid vehicles.

NOMENCLATURE

Abbreviations

BMEP	Brake mean effective pressure
BSFC	Brake specific fuel consumption
EAT	Electric assisted turbocharger
EDC	Electrically driven compressor
EGR	Exhaust Gas Recirculation
NA	Natural aspiration
PID	Proportional-integral-derivative controller
VGT	Variable geometric turbocharger

Notation

Notation	Description	Unit
F	Force	N
N	Rotational Speed	RPM
p	Pressure	Pa/bar
P	Power	kW
t	Time	s
T	Temperature	K
m	mass	kg
W	Work	kJ
μ	Efficiency	
C	Specific Energy	kJ/kg

2 BACKGROUND

In the last few years, electric boosting system attracted more attentions [8-10]. Electric assisted boosting systems are a new design of mild hybrid powertrain which use electrical energy to provide some or all of the engine air-flow. This increase in airflow allows a greater quantity of fuel to be burnt in the combustion chamber, meaning that the electrical energy used in the air-path results in additional power at the crankshaft. This can ultimately result in higher efficiency vehicles through downsizing or down-speeding. Many electric airpath configurations are possible, but they are all fundamentally based on using an electric motor to provide mechanical energy to a compressor. There are 3 different types of electrified boosting systems:

1. Separate electrically driven compressor
2. Mechanically decoupled turbocharger
3. Electrically assisted turbocharger

Electrically driven compressor is generally used in a multi-stage application with a turbocharger. It is used to increase the maximum boost pressure at low engine speeds and improve the transient response [8-9, 11-13]. Turner [8] introduced an experimental based ‘Supergen’ system which mounted a compressor with electric motor and engine crankshaft, together with another turbocharger, this system overcomes the limit of low speed torque that had been observed in a two-stage turbocharging system. An increase of about 1.3 to 4.3% system efficiency in part load condition was achieved. Pallotti [11] presented a simulation and experimental study where an electric compressor was used to downsize a 1.6L petrol engine to 1.4L. The smaller engine achieved a similar performance in terms of engine torque and reduced fuel consumption on NEDC cycle by 12%. In addition, about 1 to 1.5s transient time improvement was achieved in 60-100km/h and 80-120 km/h accelerations. The system was based on a 12V electrical supply and drew about 200A current which was double the expected value. This level of electrical power consumption is much better suited to a 48V system.

Decoupled electric systems are composed of an electrically driven compressor and an electrically braked turbine linked via an electrical bus. These offer more degrees of freedom as the speeds of the turbine and compressor can be set independently to promote boost or energy harvesting [7, 14-16]. Liu [7] studied the performance of such a decoupled electric boosting system based on a validated 2.0L gasoline engine model, the whole system efficiency can be improved up to 1.5% and the average power generated during different driving cycles can be up to 0.23kW, however, the drive cycle model in this research didn’t consider transient process, so that the conclusion for energy saving about this system is over-optimistic.

Electric assisted turbochargers are a conventional mechanically coupled turbocharger with an electric motor/generator mounted to the main shaft. This system combines the mechanical efficiency of a conventional turbocharger with the ability to recuperate exhaust energy and improve transient performance [10, 17-20]. Arise [19] built up a simulation model for this system, there is a 4.6% CO₂ reduction for NEDC cycle comparing with similar turbocharged engine model. Dimitriou et al. [20] studied the transient performance of electric assisted system on step load and drive cycles, there is a 70% to 90% time improvement in transient process for specific engine torque and power target, more than 1kW average power can be generated in different drive cycles, though electric losses were not considered in his simulation. Terdich et al. [17] studied similar system in both simulation and experiment, cooperated with Honeywell. In his thesis, the issue for this technology is packaging, controlling and heat transfer management.

In this research, an airpath to be used within a 48V mild hybrid powertrain is studied, it has a VGT turbocharger and electrically driven compressor, together with 2 stage EGR for emission reduction. The aim of this paper is to understand the opportunities and trade-offs in such kind of electric boost system, mainly discuss the system steady state and transient performance affected by EDC.

3 METHODOLOGY

The work makes extensive use of the modelling environment GT power to explore the different configurations and control of the air path system. An experimental test facility is used for experimental validation of the simulation results.

3.1 Engine configuration and Simulation model layout

This research is based on a multi-stage electric boosting system for a 1.6L Diesel engine which has been downsized from a 2.0L baseline engine. The 1.6L engine air-path is composed of two EGR loops (low and high pressure) and a two-stage boost system, comprising an electrically assisted compressor and a VGT turbocharger. The air path layout is summarised in Figure 1. The electrical energy needed to drive the EDC can be taken from the battery or the engine alternator. Engine inlet intercooler location (pre- or post- EDC) is also a design variable to be discussed. The main target for this paper is to investigate how the system configuration and control affect the engine performance.

The model was configured within the GT-Power simulation tool (v2017, Gamma Technologies, LLC, Westmont, IL, USA, 2016). The combustion model was build based on the flowing elements [21]:

- Imposed heat release profiles derived from measured combustion pressure data.
- 1D representation of manifolds and ducting validated against crank angle resolved measurements of pressure pulsations within the intake and exhaust system
- Experimentally tuned heat transfer coefficients validated against experimental data.

The airpath model included characteristic maps for the VGT, turbocharger compressor and electrically driven compressor. The electrically driven compressor is driven by a simple electric motor model. A simple alternator model is included in the case of energy being drawn from the crankshaft. An EDC bypass and control valve is also included. Boost is delivered according to the following control principles:

- At high engine speeds, turbocharger compressor boost target was set to achieve the desired engine torque and EDC was bypassed.
- At low engine speeds, turbocharger compressor was set with consideration of compressor surge. This introduces a trade-off between reducing the electrical load of the EDC by operating the turbocharger compressor closer to surge or increasing the surge margin but requiring higher EDC power.
- During transients the EDC can be used to reduce the boost error during periods of turbo-lag.

There is some level of flexibility in the control of the boosting system as the total boost pressure can be provided either from the turbocharger compressor or from the electrically driven compressor. The turbocharger compressor is controlled by the VGT guide vanes and must be selected with attention on possible surge. The VGT position will also affect the engine back pressure. The EDC is controlled using the electrical power but does not affect engine back pressure. Its operation should be selected bearing in mind the maximum electrical power available. In this paper, the trade-off between VGT and EDC operation will be discussed in full load and low speed condition.

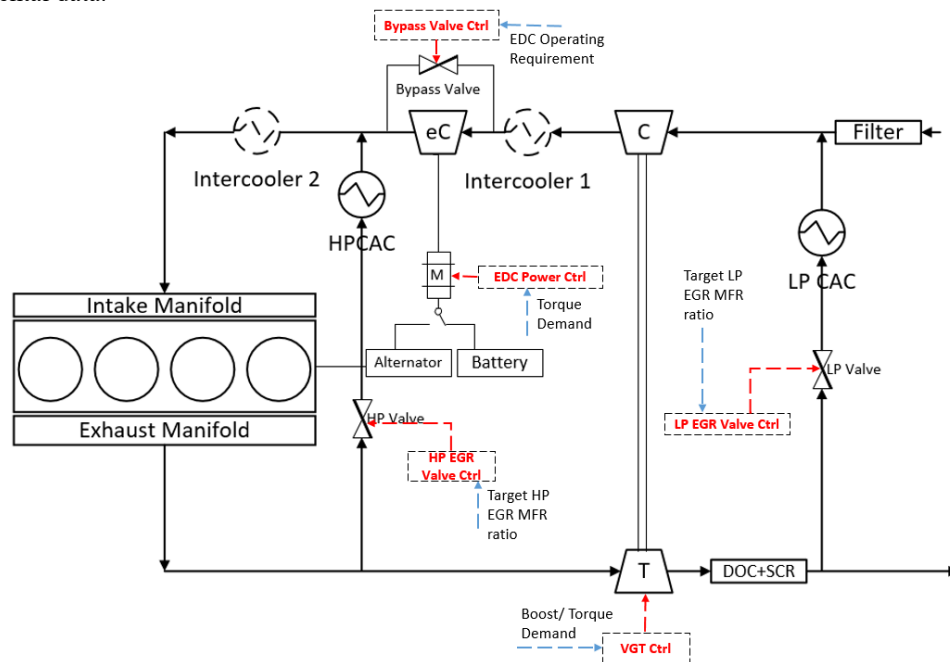


Figure 1. Engine Airpath Layout

This air path model was controlled based on the following principles, controlling structure is shown in Figure 1:

- VGT guide vanes were controlled using a PID controller targeting a specified compressor outlet pressure and respecting the compressor surge limit.
- The fuelling was determined based on an Air Fuel Ratio limit which was also speed dependent.
- EDC controller adjusts the EDC speed for engine torque demand by increasing inlet pressure.
- Three valves including two EGR valves and EDC bypass valve are used for controlling the flow through each path.

In summary, the engine output power is adjusted by changing target boost pressures for both turbocharger compressor and EDC.

3.2 Experimental facilities

In the THOMSON project, a transient air path testing facility was built using a 2.2L diesel engine as a source of thermal power to drive the turbocharger turbine. The major function for this test rig is to measure the boost components behaviour in steady state and transient conditions. The test rig uses the 2.2L diesel engine and an external boosting system to provide power to the turbocharger turbine. The intake side of the airpath operates against a back-pressure gate valve in a similar way to a turbocharger gas-stand. This decouples the link on-engine between turbine power and intake system performance and allows for a broader range of airpath operating conditions to be explored. The use of the engine as a gas generator means very

rapid changes in turbine inlet temperature can be created as this is controlled by the fuel injection pulse width. Figure 2 and Figure 3 shows the test rig structure of the engine gas stand facilities. A 30 litre settling tank installed at the engine outlet side to reduce the pulsating flow and to increase the accuracy of the turbine inlet temperature and pressure measurements. The facility can independently control turbine and compressor/intake side boundary conditions.

The air-path shown in Figure 1 was recreated on the test facility in order to provide an engine independent assessment of the boosting system performance. Both EGR circuit are also recreated along with a water charge air cooler which can be located at different positions in the system.

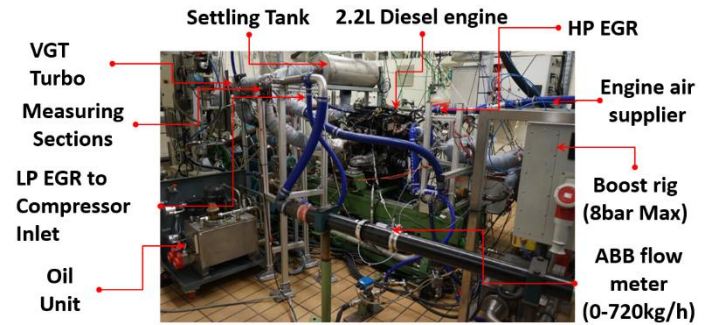


Figure 2. 48V system airpath test rig

The EDC motor is connected to a 48V power supply system and the dSPACE/Control Desk (Matlab toolbox) will send out a proportional CAN signal to manage the rotating speed.

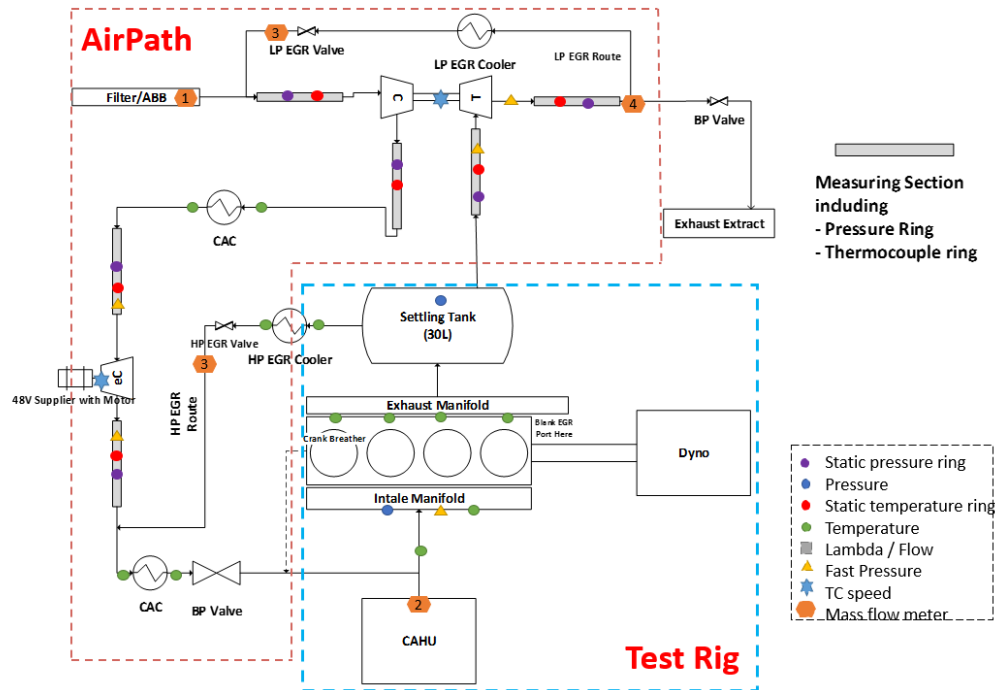


Figure 3. Test rig structure layout

3.3 Airpath design

The work is split into two major sections, the first looking at full load operating conditions and the second looking at transient response. For the full load operation, the following studies were conducted:

1. An analysis of the trade-off between turbocharger and electrically driven compressor control to deliver the target boost pressure.
2. An analysis of EGR capabilities close to the limiting torque condition.
3. A comparison of different intercooler locations with a focus on the operating temperatures of the electrically driven compressor and on engine breathing.

The transient simulations assessed how the EDC can help to improve the engine transient performance. In this part, the transient simulations are based on the validated part load data, the transient operating points is from 2000RPM 5bar part to 2000RPM full load condition. During the transient, a number of control actuators are available to influence the transient response of the engine (highlighted in Figure 1):

- EDC power level (kW used and duration of activation)
- EDC bypass valve (duration of time using EDC and bypassing EDC include delay before closing)
- Turbocharger VGT (position and duration in over-closed position)
- EGR valve closing times (both HP and LP valves)

The EDC can also be used to increase air flow during a transient event which can be used to improve emissions control (such as increasing the air to fuel ratio to reduce soot). The potential of the EDC to deliver these increased AFRs will also be investigated, based on the same control parameters described above.

4 RESULTS AND DISCUSSION

4.1 Turbocharger and EDC component mapping

In the first stage of experiment, steady state mapping experiments were conducted for the turbocharger and EDC. These experiments were compared to standard gas-stand measured maps to ensure the new air path test rig provided consistent results. The experimental mapping result for turbocharger compressor are shown in Figure 4. Some mass flow offsets exists in the high-pressure ratio region, however this result is acceptable.

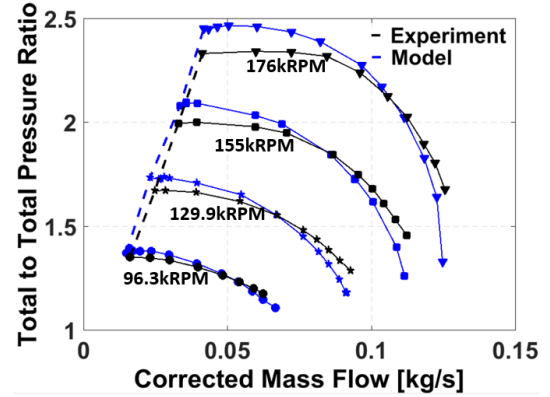


Figure 4. Compressor Map

The turbocharger turbine in this paper is a VGT turbine. In this process, the turbine inlet temperature is set to be 823K, VGT guide vane position is kept for specific value for each single rack position line. The turbine map is shown for different VGT position in Figure 5.

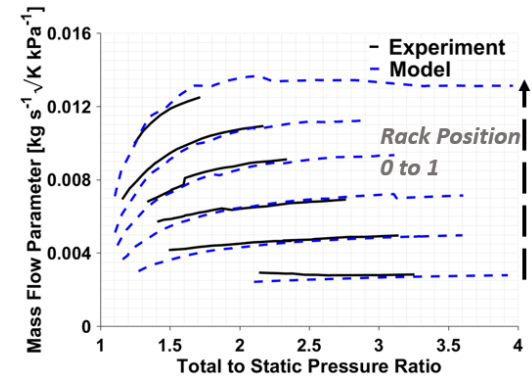


Figure 5. Turbine Map

Figure 6 compares the EDC maps from both facilities. The surge line results differ slightly between the two datasets but there is overall good correlation between the two.

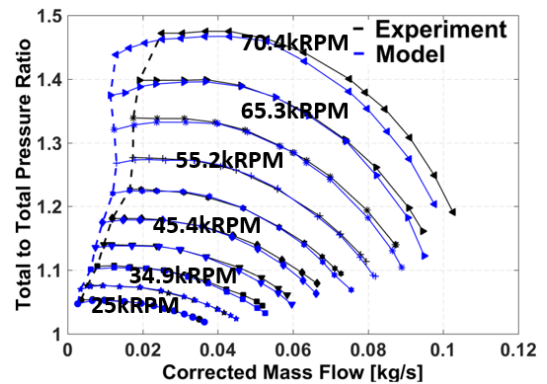


Figure 6. EDC Map

4.2 Steady-state air path mapping

4.2.1 Air path operating principle

The downsized 1.6L engine is an evolution of a lower power 1.6L engine which provided the basis for the new air path. The turbocharger on the older engine was replaced with a larger device which allows for the increase in engine power. However, the larger turbocharger reduces the low speed limiting torque due to larger turbine being unable to create sufficient backpressure. Therefore in the engine speed range 1000-1500rpm, the EDC provides the additional boost pressure. The control methodology based the assumption that VGT is always controlled to deliver the largest pressure ratio it can achieve. For a given engine air flow requirement, this limit is effectively defined by the surge line of the turbocharger compressor. The rationale for this approach is that thermal energy in the exhaust is free and its use should be maximised. The maps and engine operating points with speed are shown in Figure 7. As can be seen, for engine speeds of 1500rpm and below, the turbocharger compressor is operating along the surge line and therefore limited in pressure ratio.

The electrical power for the EDC can be obtained from a battery (without loading the engine crankshaft) or provided from the alternator (which increases the load on engine crankshaft). The structure can be seen from Figure 1. If the alternator is used, then the to maintain the same brake torque the engine must produce a higher indicated torque which is achieved by burning more fuel, and therefore increasing the air flow requirement for a fixed limiting air-to-fuel ratio. An unexpected consequence of this is a reduction in the electrical power required to drive the electrically driven compressor. This is explained because when using the alternator, the higher air flow shifts the operating point on the turbocharger compressor towards the higher mass flows (towards the right). This in turn means that a higher pressure ratio can be achieved within the surge limit (Figure 7).

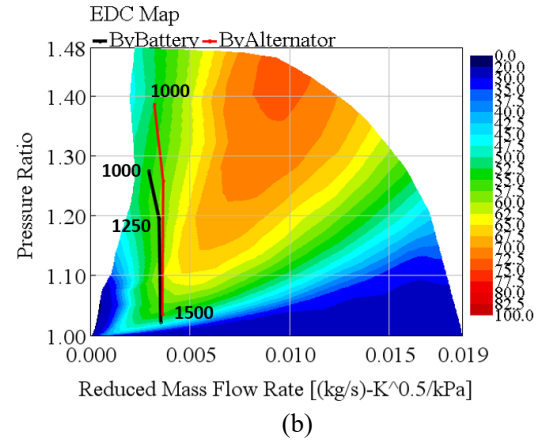
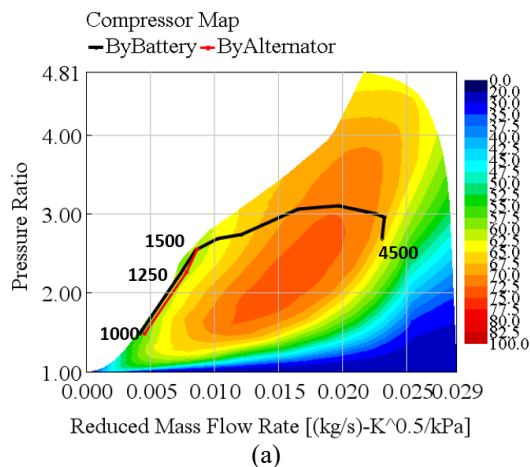


Figure 7. (a) Compressor operating points. (b) EDC operating points

Despite the lower electrical power, the specific fuel consumption is of course increased when using the alternator because the electrical energy is no longer “free” as in the case of the battery (Figure 8). From Figure 7 and Figure 8, when EDC is driven by alternator which connecting with crankshaft, system BSFC will decrease as EDC delivers more boost, when EDC is driven by E-motor, the energy comes from battery, an electricity about 0.5 to 2kW is needed in the case. It is justified to consider that the electrical energy is free in the case of the battery system as without considering full drive cycle operation it is not possible to determine the origin of this energy. In a 48V hybrid vehicle it is reasonable to assume that kinetic energy recovery will be available during braking and if this is used to subsequently drive the EDC than it is effectively free. This drive cycle based energy flow analysis will form part of future publications within the Thomson Project [22]. For this reason, the next sections of this paper will focus on the battery condition, simplified as an ideal electrical power source.

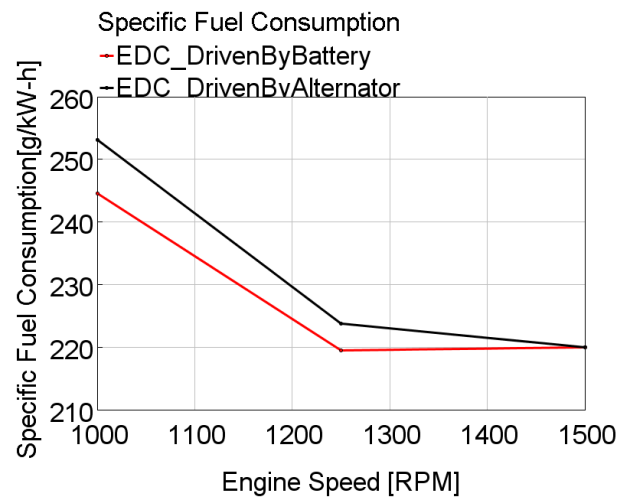


Figure 8. System BSFC under different EDC controlling methodology.

The three limiting torque operating points at 1000, 1250 and 1500rpm have been run experimentally on the air path test rig: the measurements are compared to the simulations in Figure 9. The results show a good match between 1D simulation and experiment. Further reasearch on EDC performance will focus on these 3 operating points.

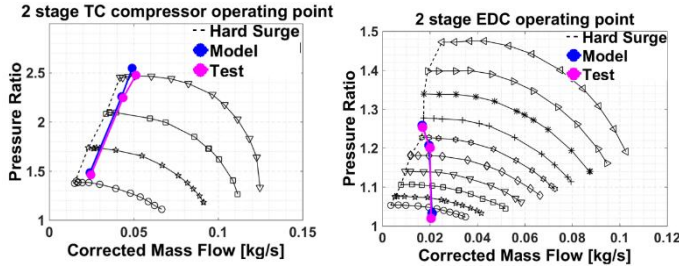


Figure 9 Experiment results comparing for 3 operating points. (a). Compressor operating points. (b). EDC operating points

4.2.2 Control trade-off of the VGT and electrically driven compressor

To investigate the trade-off between turbocharger and EDC use to provide boost pressure, a DOE simulation has been conducted with different turbocharger outlet boost targets. Figure 10(a) shows the compressor operating points at steady state condition as the changing of boost target between 100% and 85% of it nominal value. VGT turbine guide vane rack position is also shown in Figure 10(b), as the VGT guide vane opened the compressor pressure ratio reduces as well as engine backpressure.

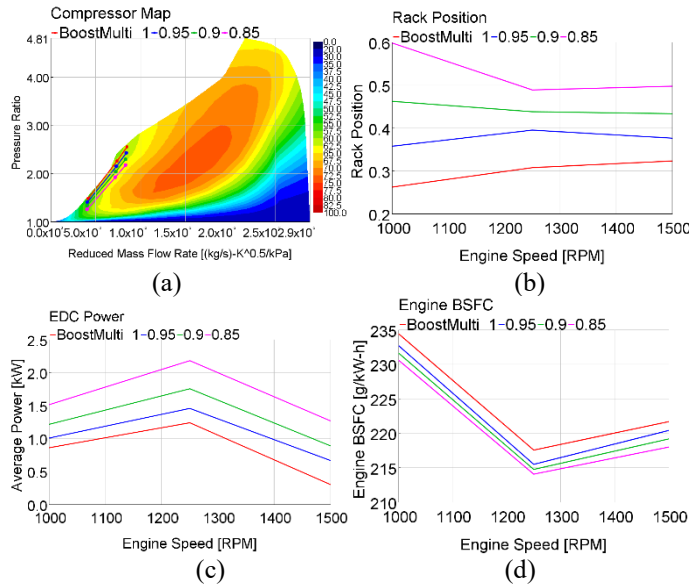


Figure 10. (a). Compressor operating points under different VGT rack position. (b). VGT rack position. (c) EDC Power. (d) Engine BSFC (BoostMulti means how much boost target was set for turbocharger comparing with the initial value(BoostMulti 1))

As the turbocharger reduces the amount of work it provides to the intake air, the EDC work needs to increase to compensate for this loss: The corresponding power consumptions are shown in Figure 10(c). The electric power needed is increased as high as 2.2kW.

By opening VGT guide vane further, less fuel is burnt to provide the same output brake torque as pumping losses are reduced; the engine BSFC is therefore reduced (see Figure 10(d)). However, this bsfc does not capture the increase in power for the EDC and it is important to understand where this electrical energy originates. If this is considered to come exclusively from kinetic energy recovery, then it is reasonable to omit it from the stated engine efficiency. If it is a result of increased alternator loading at a different time period, then the situation is more complex as the respective benefits depend on the trade-off of electric component efficiency and changes in engine efficiency due to the charge.

This is the compromise between EDC power consuming and engine pumping loss. Figure 11 is the equivalent system BSFC and its calculating method, considering EDC power and electric efficiency (assumed 60%). The BSFC difference is less than 0.5%.

$$\text{System BSFC} = (m_{\text{fuel}} + P_{\text{EDC}} / (C_{\text{fuel}} * \mu_E) / P_{\text{engine}})$$

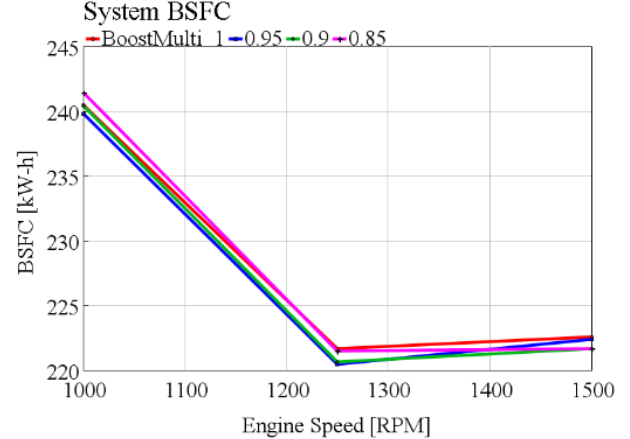


Figure 11. System equivalent BSFC and calculation method

The trade-off between VGT and EDC has also been evaluated on the test rig. Similar boundary conditions to the simulations have been designed for the tests. In the test, The EDC speed will be varies in increments, starting at 5000RPM without changing all the other conditions. The VGT will then be opened gradually until the target boost pressure is achieved. Figure 12 shows the relationship between VGT rack position and EDC power when they are operated for target boost pressure for both Simulation and Experiment. The similar trade of can be observed from those results comparing with simulation, a 0.1 rack position increasing will lead to a request of 0.2kW to 0.55kW more EDC power.

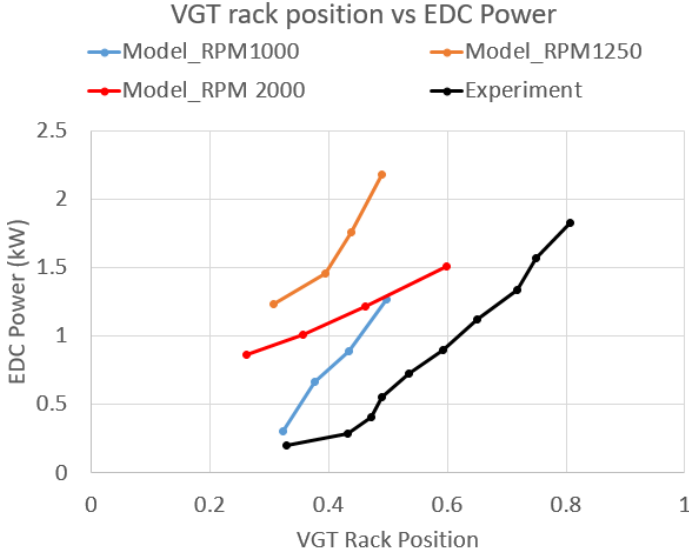


Figure 12. VGT rack position and EDC power under the same target boost pressure

4.2.3 EGR at full load

The ability to flow EGR near the limiting torque curve is investigated due to its importance in emissions control for Real Driving Emissions legislation. In this stage, 0%/5%/10% LP EGR are used individually on engine speed 1000, 1250 and 1500RPM. Note it is not possible to flow HP EGR at these conditions because the EDC causes a higher intake manifold pressure than the exhaust manifold. When introducing EGR, the turbocharger can be operated with the same target compressor outlet pressure, or re-calibrated to operate on the surge line. This re-calibration is necessary because the addition of LP EGR increases the mass flow through the compressor. The turbocharger compressor operating points with EGR are shown in Figure 13 for both these conditions.

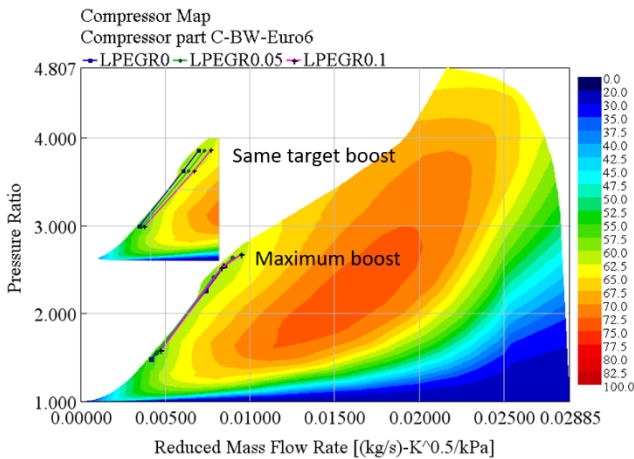


Figure 13. Compressor Map for maximum boost and (inset) same target boost condition

When turbo compressor is operated for the same target boost, the EDC power must be increased to deliver higher intake manifold pressure to maintain the same fresh air flow despite the presence of EGR. For the target torque Figure 14 shows the change in EDC power with increasing EGR: the EDC power needed is nearly 2kW at 1250rpm and 10% EGR.

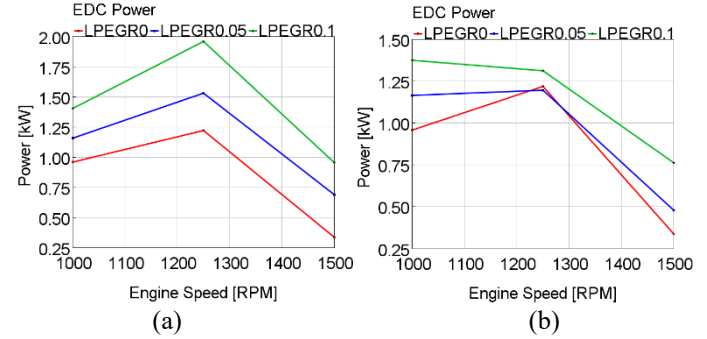


Figure 14. (a). EDC Power requirement when introducing LP EGR without changing the turbocharger outlet pressure target. (b). EDC Power requirement when introducing LP EGR whilst operating the turbocharger compressor on the surge limit

For the case where the turbocharger compressor is recalibrated to operate close to surge, the increase in EDC power is significantly less (less than 1.5kW at 10% EGR). However the engine BSFC will become worse because more closed VGT lead to a higher backpressure and makes the engine efficiency lower.

Based on those results above, we can have the conclusions:

1. Higher EGR rate leads to higher torque losses, either EDC or VGT should be operated for higher boost, EDC needs electricity, lower VGT rack position lead to higher engine backpressure.
2. By introducing the EGR, engine inlet total mass flow rate will be increased, turbocharger compressor is able to deliver more boost instead of being surge in low speed condition.

4.2.4 Effect of Intercooler location

The intercooler location will affect EDC inlet temperature so that the EDC efficiency and boost requirement will change. It is necessary to study how different intercooler location changes the EDC work status and engine inlet temperature. The different intercooler location layouts have been shown in Figure 1, the intercooler can be:

1. In between the turbocharger and EDC.
2. Downstream of EDC and turbocharger.

Figure 15 shows the temperature at different locations at EDC and engine inlet side. When intercooler located after EDC, EDC inlet temperature will be much higher as the compressed air from VGT compressor was not cooled down, the engine inlet temperature will be lower than when the intercooler is upstream of the EDC. This difference is only noticeable when the EDC is active (i.e. below 1500rpm).

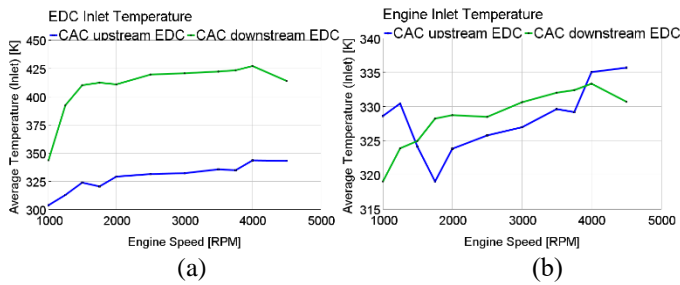


Figure 15. (a). EDC Inlet Temperature. (b). Engine Inlet temperature

Figure 16a shows that the intercooler location has little impact on the turbocharger compressor operating points. In contrast, Figure 16b, shows that for the EDC, operating point changes significantly due to changes in the inlet temperature which affect the corrected speed and mass flow.

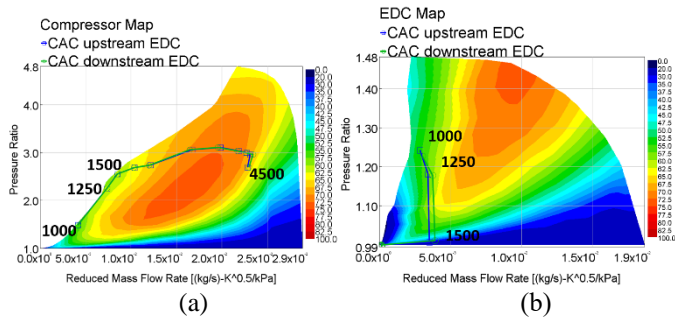


Figure 16. (a). Compressor map and operating points. (b). EDC map and operating points

Figure 17 shows the EDC power needed for different CAC Location, when CAC is post the EDC, the power needed is higher because the inlet air flow of EDC is hotter in this condition, on the map which means the corrected mass flow is lower, EDC needs to rotate faster for the target boost.

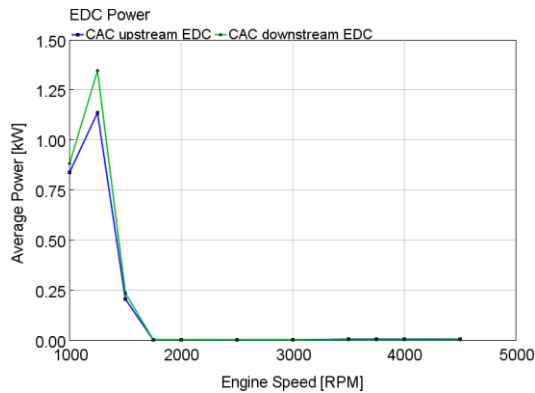


Figure 17. EDC power under different CAC location

4.3 Transient Performance

4.3.1 Engine transient response vs EDC power

Figure 18 (a) and (b) shows the first transient setting case, in order to see how different EDC power levels affect the engine torque response during a 2000 rpm fixed load step. Three power setting of 1, 2 and 3kW are compared and reduce the 5-90% load response time by 0.95s, 1.42s and 1.56s respectively.

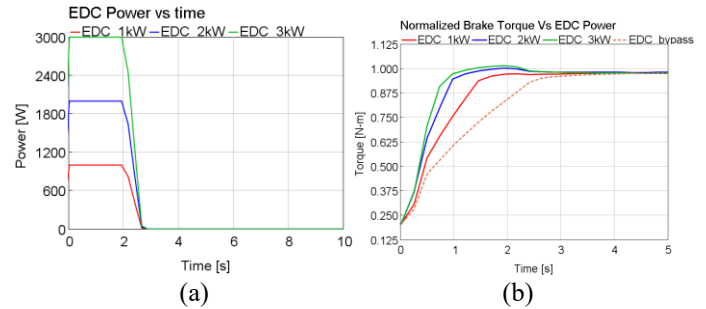


Figure 18. (a). EDC power input during transient; (b). Normalized Engine Brake torque with different EDC power.

Figure 19(a) and (b) show the effect of EDC on-time. It can be seen that above 3s there will be very little additional benefit from extended use of the EDC.

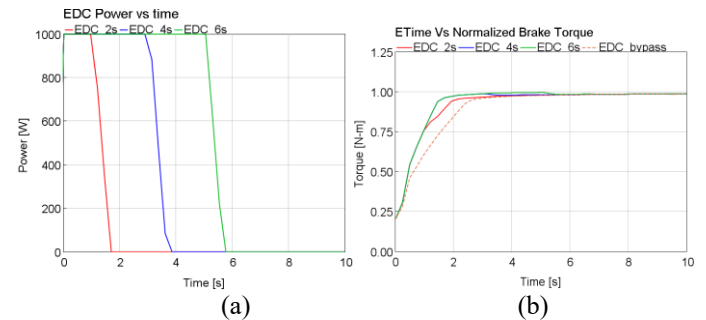


Figure 19. (a). EDC Power vs time; (b). Normalized engine torque transient response.

Figure 20 shows the response time for achieving 95% engine target load under different EDC power settings (power value and continuing time). The x axis represents the total amount of electrical energy used by the EDC which will increase with EDC power level and/or EDC on-time. However diminishing returns can be seen. Typically, at 2000rpm full load the EDC is not active, however here it is shown how it can improve transient response. The inclusion of the EDC reduces the time to 95% target torque from 2.3s to around 0.75s, though 7kJ more electricity was consumed. If the EDC power is the same but work for different time, most of the benefit occurs in activating the EDC over the first 0.5-1s of the transient.

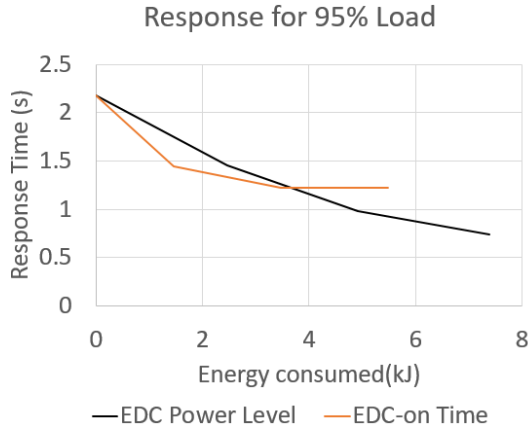


Figure 20. Response time for different EDC power and power continuing time

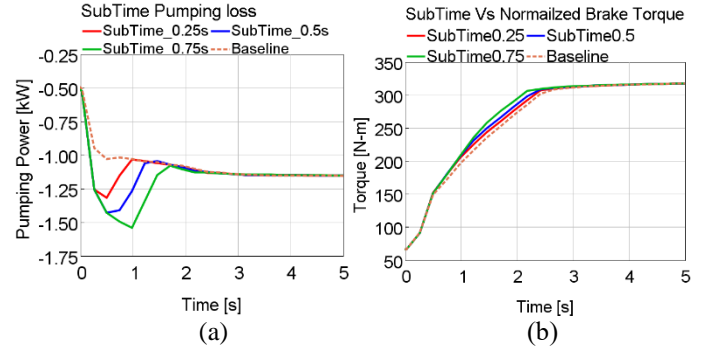


Figure 22: a. VGT Rack position ; b. Engine brake torque.

Figure 23 summarises the relationship between pumping energy and engine transient time for the different VGT strategies.

4.3.2 VGT rack control

The VGT can also be used to improve transient performance by “over-closing” the guide vanes to spool up the turbocharger faster. However this will increase engine back-pressure which in turn will reduce torque response. Figure 21 shows the VGT rack position over time and its consequent engine torque response. When rack position is 0.3 and 0.2, the torque response is been increased by 0.12s and 0.3s respectively. However when it further reduced to 0.1, the torque response improvement is only 0.2s compared to the baseline.

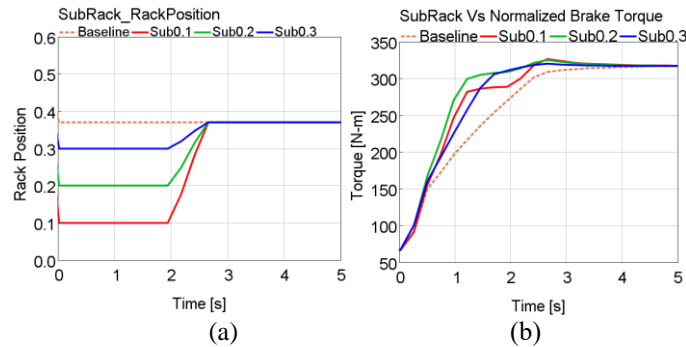


Figure 21. (a). VGT Rack position. (b). Engine brake torque.

The duration of VGT “over-closing” is also of interest. Figure 22 shows the result if VGT is held in a lower rack position for different time range (0.3s, 0.6s, 0.9s). Holding the VGT guide vane in lower position for longer time can improve the transient by up to 0.25s.

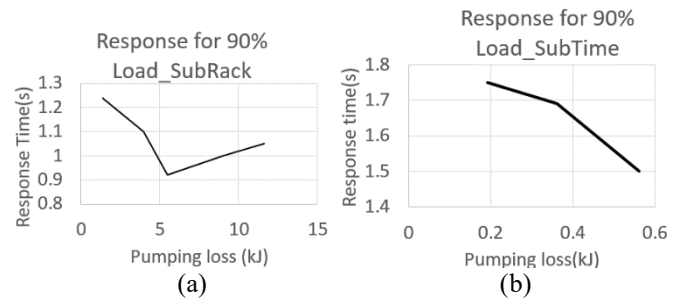


Figure 23. Pumping energy against response time for (a) different rack positions and (b) different “over-closing” times

Based on all those results above, the transient response can be increased both by the assistance of EDC or by over-closing the VGT. In Figure 20, when the transient response time was reduced from 2.25s to 1s, the extra electricity consumed by the EDC is about 5kJ. When it comes to over-closing the VGT, the increased pumping loss is also close to 5KJ. However, what cannot be ignored is that over-closing the VGT will reduce the engine peak torque, when rack position is lower than 0.2, the transient time will be increased as because the backpressure is too high.

4.3.3 Air fuel ratio effects on transient performance

Air to fuel ratio (AFR) is one of the main factor when dealing with diesel engine soot emissions. These emissions are more likely to occur during a rapid load transient where the fuelling is limited by an AFR limiter. Therefore, for a given change in engine torque, the sooner the engine can move away from this limit, the easier it will be to reduce soot emissions. By using the EDC to vary the air flow during the transient, an increase in airflow can be achieved without applying backpressure to the engine. This in turn will increase the AFR which gives possibilities for controlling emissions at source in the cylinder. This approach was analysed in the simulation environment.

For simulation setting, the transient process happened at time 0s, engine speed 1250RPM, from 5bar BMEP to full Load condition, Figure 24 shows the relationship between engine brake torque transient time and engine AFR ratio, in this case, VGT rack position is fixed to keep the same, however engine fuel rate and EDC driven power is different for the same target torque in each case. As the AFR limit becomes higher, less fuel will be cost in this case, but more electric power will be needed for boosting. The transient response speed is similar, which was effected by both AFR limit and EDC power. These results show that by using the EDC to provide additional air flow, the same engine torque response can be achieved with reduced air to fuel ratios. Figure 28 shows that an increase in AFR of 1 requires approximately a 0.4kW increase in EDC power.

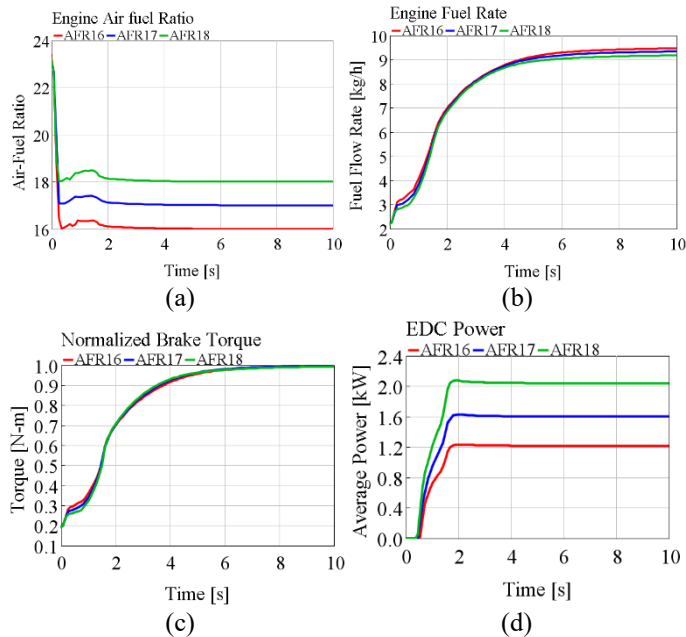


Figure 24. (a) Engine Air fuel ratio. (b) Engine fuel rate. (c) Engine brake torque transient response. (d) EDC Power.

5 CONCLUSION

The research in this paper studied an electrified airpath system for use within a 48V mild hybrid powertrain. This work is conducted as part of the EU funded project 'THOMSON', this paper aims to study the performance of the electrified airpath system for a 1.6L diesel engine, understanding the trade-offs of different components. Experiments were conducted with the full airpath system to validate some of the experimental findings. The test rig is built based on a 2.2L diesel engine for enough exhaust power required taking used by turbine.

A two stage airpath with VGT turbocharger and a high pressure electric driven compressor (EDC) was studied. The trade-off between electrical energy consumption of the EDC and pumping energy to drive the VGT was discussed. By the opening

of VGT from 0.1 to 0.3, engine pumping loss is reduced by 7kW, however, to maintain engine brake output, 2kW more electricity is needed to drive the EDC.

The location of intercooler was analysed in terms of the EDC work and engine intake manifold temperature. When the intercooler is located between the compressor and EDC, EDC inlet air is cooled down by over 100K which can help increasing the boosting efficiency, and reduce the electric energy consumption for the same boost pressure target. However this configuration will have higher engine inlet temperature which will impact on engine volumetric efficiency, ultimately reducing engine output torque.

The effects of EDC power, VGT rack position and AFR limit were studied during transient load steps. Driving EDC in higher speed, closing VGT more than target position during transient, operating the AFR to lower limit, these operations can increase the time to reach target torque, the response time has been reduced by 0.1s to around 2s, however, all these controlling methodologies will decrease the engine efficiency.

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